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Nature Geoscience 2015, 8(7), 493-494.

Initiation of the Lusi Mudflow Disaster

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The Lusi mudflow on Java is a unique disaster in which mud suddenly erupted in an urban area. Nine years of continuous eruption has displaced 39700 people and cost over US$2.7 billion in damages and disaster management. Intense debate has focused on whether the eruption was naturally triggered by the Mw6.3 Yogyakarta earthquake (2 days prior, 260 km away)[1,2] or was the result of drilling operations in the nearby Banjar Panji-1 (BJP-1) well[3,4]. Arguments surrounding the 'earthquake triggering' hypothesis are centered on whether the Yogyakarta earthquake could trigger liquefaction of the Kalibeng clay formation (900-1870m depth), the source of solids in the erupting mud[1,2]. Here we use subsurface gas measurements from BJP-1 to show that there was no significant change in gas release after the earthquake, demonstrating that liquefaction did not occur. Moreover, comparison of subsurface and erupted gas compositions indicates that the initial eruption expelled fluid from a deeper source than the Kalibeng Clays. Taken together, these two observations provide key insight into

the initial plumbing system of the Lusi mudflow and allow the earthquake-triggering hypothesis to be directly tested.

Clay liquefaction is initiated by changes in effective stress (stress minus fluid pressure), and these same changes will also cause the widespread release of formation gases by dissolution (effective stress drop) or compaction-associated fluid expulsion (effective stress increase)[1,2,5]. Indeed, large gas releases are observed during mud volcano eruptions, and liquefaction at Lusi would have been immediately associated with extensive gas release[2,6].

The BJP-1 borehole was located just 150 m from what became the main vent of the Lusi mud volcano and, being uncased from 1090 to 2833 m depth, was directly exposed to almost the entire thickness of the Kalibeng clays[3,4,7] (Figure 1). A range of gas measurements were taken continuously during all drilling operations, starting from March 2006 up to the day of the Lusi mud eruption (29/5/2006)[7,8]. Gas measurements obtained from the BJP-1 well provide a unique opportunity to determine baseline formation gas data prior to the Yogyakarta earthquake and Lusi eruption, and to make a detailed examination of the response of the Kalibeng clays immediately after the earthquake.

We use daily maximum gas measurements and continuous depth-based measurements[9] to characterize the range of gas values observed in formations encountered by BJP-1 (Figure 1; Supplementary Table 1), and focus on the maximum values observed in the 48 hours before, and 24 hours after, the Yogyakarta earthquake[7,8] (Supplementary Table 2). No increase in subsurface gases was measured in the 24 hours after the earthquake, which covers almost the entire period between the earthquake and the major fluid influx ('kick') into the BJP-1 wellbore[7]. Indeed, maximum gas readings after the earthquake are noticeably lower than in the two previous days, but are within the normal range of gas values recorded from the volcanic and volcaniclastic formation under the clays, and particularly the calcareous volcaniclastic sequences below 2600m. The post-earthquake gas readings from BJP-1 are significantly lower than typical measurements in the Kalibeng clays, particularly with regards to heavier gases (C_4-C_5); that are diagnostically high in this formation[8]. It is important to note that increased gas levels would be expected regardless of whether the earthquake had induced dilation (through gas exsolution) or compaction (higher pore pressures causing increased fluid and gas flow into BJP-1)[2,8]. Any liquefaction or remobilization would also cause wellbore instability in the Kalibeng formation and clay cavings in the drilling mud, and neither were detected in the period between the earthquake and the kick in BJP-1[4,7,8].

The gas data from BJP-1 also provide new evidence to identify the fluid source driving the initial Lusi mud eruption, a critical difference between published models for the initial eruption[1,2,3,4,6,7,10]. Each formation encountered by BJP-1 has a distinct range of gas readings that can be used to 'fingerprint' the formation from which fluids emanated (Supplementary Table 2). Of particular relevance is the observation of minor H_2S from BJP-1 several hours before the earthquake, just 20 meters from the bottom of the BJP-1 well[8]. H_2S was then observed coming from BJP-1 during the drilling kick, and also from Lusi in the initial days of the eruption[4,7,8,10]. H_2S was not observed at any time while drilling the Kalibeng clays, despite direct gas measurements from ~60m^3 of Kalibeng cuttings[8]. The only known source of H_2S in the East Java Basin is from Tertiary carbonates[8,10], such as the Miocene carbonates targeted by BJP-1, although H_2S could alternatively have a volcanic or hydrothermal origin[6]. Whilst it is not certain whether the BJP-1 well penetrated the Miocene carbonates, drilling reports state the carbonates were possibly penetrated at 2831m[7], and it is generally accepted that the bottom of BJP-1 was within, or in communication with, these carbonates[3,4,7,8,10]. The observation of H_2S near the base of BJP-1 prior to the earthquake thus provides compelling evidence that an initial source of fluids for the Lusi eruption was significantly deeper than the Kalibeng clays.

The presence of a deep fluid source for the Lusi mudflow has been previously demonstrated from the analysis of erupted gas samples (collected months to years after the eruption began)[6]. This observation led to the hypothesis that a natural hydrothermal system existed at the Lusi site, and that deep fluids had 'pre-charged' the Kalibeng clays, priming the clays for remobilization by the Yogyakarta earthquake[6]. However, the observation of deep H_2S at the base of BJP-1, and absence of any measured H_2S in the Kalibeng clays, suggests that there was no pre-eruption fluid communication between the Kalibeng clays and the Miocene carbonates (or deeper formations). Whilst it is possible that Lusi had an initial hydrothermal influence, the gas data herein indicates that this must be a deep system, within the Miocene carbonates or deeper.

Published earthquake triggering models require the primary, and deepest, initial source of erupting fluids to be the Kalibeng clays[1,2], whilst published models for

Lusi being a natural hydrothermal system involve pre-eruption migration of deep fluids into the Kalibeng clays[1,6]. The absence of any evidence of liquefaction or deep 'pre-charging' of the Kalibeng clays thus directly contradicts natural triggering models for the Lusi disaster. The gas data indicate that initial driving fluids were from the Miocene carbonates (or deeper), and that a fluid pathway through 940 meters of low permeability volcanics/volcaniclastics[8] suddenly developed immediately prior to the Lusi eruption. This matches with the drilling trigger hypothesis[3,4,7,10], which proposes a deep initial source of fluids for the Lusi mud flow, and that these flowed into the Kalibeng clays via the open BJP-1 wellbore.

In summary, measurements demonstrate that no gas flux increase occurred at any time in the 24 hours following the Yogyakarta earthquake. These results reveal that the earthquake did not trigger Kalibeng clay liquefaction at the Lusi location. Furthermore, gas data indicate that initial Lusi fluids were sourced from Miocene carbonates[8,10] or a deep hydrothermal system[6], and that there was no pre-eruption fluid communication between the Kalibeng clays and these deeper formations. Hence, the gas data from BJP-1 provides compelling evidence against published earthquake-triggering[1,2] and natural hydrothermal[6] models for the triggering of the Lusi mudflow. In contrast, the data support models that invoke an influx of deep fluids into the well[3,4], and hence that drilling operations initiated the eruption.

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Acknowledgments

B. Istadi is appreciated for providing data access. We thank D. Dewhurst and W. Evans for comments. The US-based authors are supported by the National Science Foundation.

Author contributions

M.T. collected the data, conducted the study and jointly wrote the manuscript with M.R. and M.M. M.R. coordinated the study and conducted gas analysis. M.M. conducted gas and seismological analysis. R.D. collected data. C.Y.W. conducted seismological analysis.

Additional information

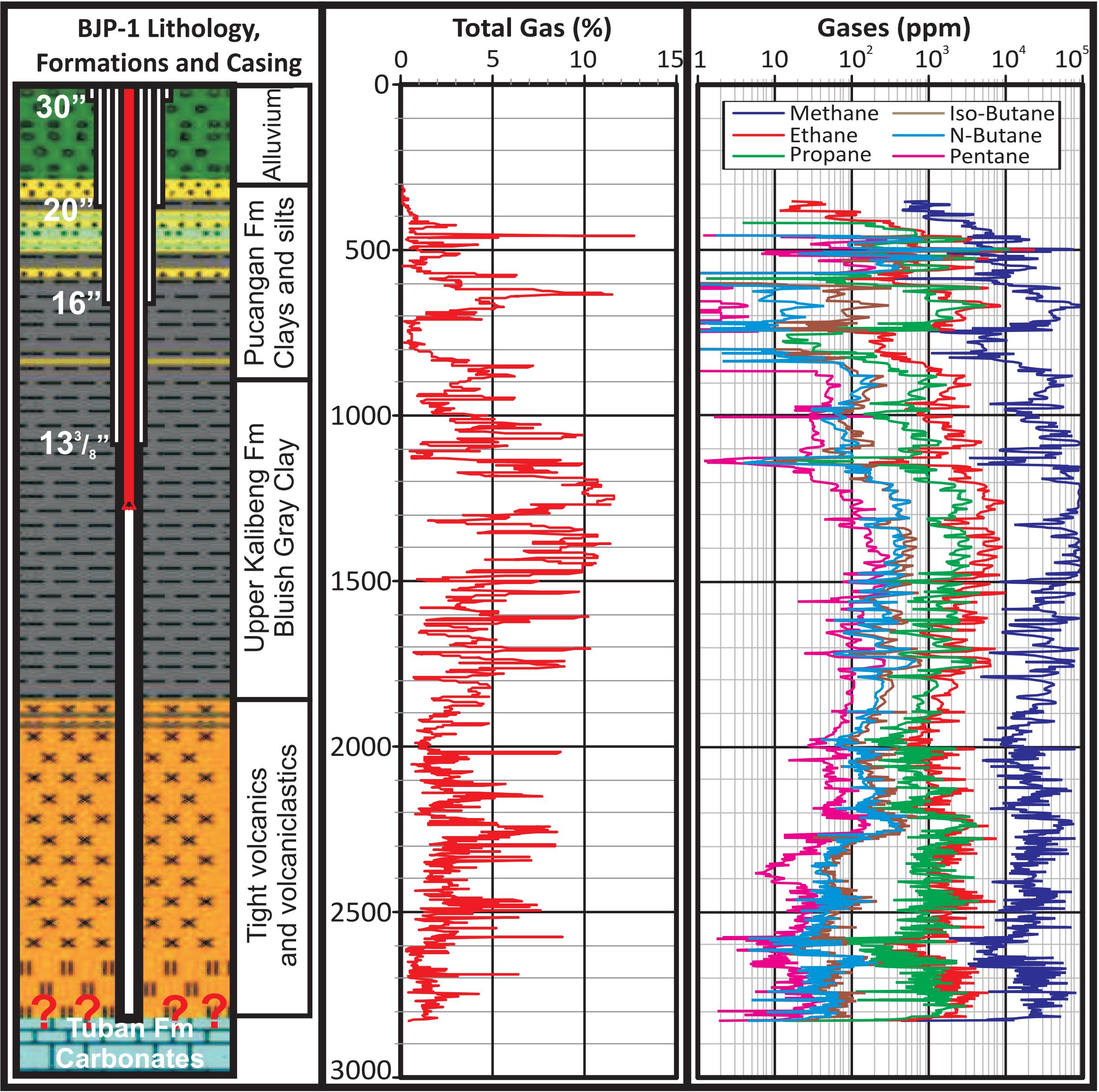
Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to M.T.

Competing financial interests

The authors declare no competing financial interests.

Figure Captions

FIGURE 1: Stratigraphy, design of the BJP-1 borehole and measured gases amounts encountered by the BJP-1 well[7,8]. Total gas is the percent of gas, by volume, extracted from drilling mud returned from a specific depth[9]. Gases data is the concentrations of individual gases from individual depths, as measured by gas chromatography[9]. Gas amounts are significantly higher in the Kalibeng clays, particularly for heavier gases (C_4-C_5), than in the volcanics and volcaniclastics (particularly the lowermost calcareous volcaniclastics below 2600m depth; Supplementary Table 1). Liquefaction of the Kalibeng clays would be associated with extensive gas release[2]. However, no increase in gas flux is observed in the 24 hours after the Yogyakarta earthquake, and gas readings are within the normal range of those observed when drilling the deep calcareous volcaniclastic sequences (Supplementary Table 2).



BJP-1 Lithology, Formations and Casing
30”
20”
16”
13 3/8”
Tuban Fm Carbonates
Alluvium
Pucangan Fm Clays and silts
Upper Kalibeng Fm Bluish Gray Clay
Tight volcanics and volcaniclastics
Total Gas (%)
0
5
10
15
0
500
1000
1500
2000
2500
3000
Gases (ppm)
1
10
10^2
10^3
10^4
10^5
Methane
Ethane
Propane
Iso-Butane
N-Butane
Pentane

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SUPPLEMENTARY TABLE 1: **Gas measurements for key formations under the Lusi mud volcano**[7,8]. Average values for each formation are stated, with typical background gas ranges provided in brackets. Gas measurements in the volcanic and volcaniclastic sequences are generally less than half of those observed in the Kalibeng clays, and the Kalibeng clays are particularly higher in heavier fractions (C_4 and C_5). *H_2S readings observed at ~2:00am on the 27/5/2006 and 20m from the bottom of Banjar Panji-1 (BJP-1) are interpreted to be from the Miocene carbonates (or deeper source) that diffused into the lowermost volcaniclastic sequences[8]. n/a indicates data not available.

Formation	Total Gas (%)	C_1 (ppm)	C_2 (ppm)	C_3 (ppm)	iC_4 (ppm)	nC_4 (ppm)	C_5 (ppm)	H_2S (ppm)
Kalibeng clays (900-1870m)	5.5 (2-12)	49997 (20000-110000)	3300 (2000-14000)	1497 (1000-3000)	304 (200-1000)	242 (200-1000)	105 (80-200)	0
Volcanics/ volcaniclastics (1870-2600m)	2.7 (1-6)	24116 (10000-80000)	1698 (500-5000)	1053 (300-2500)	158 (70-350)	121 (50-300)	51 (10-80)	0
Calcareous Volcaniclastics (2600-2833m)	1.7 (0.5-2)	23576 (5000-60000)	1712 (1000-3000)	913 (190-1800)	60 (20-90)	48 (10-80)	17 (5-30)	0*
Carbonates (≥2833m)	n/a	n/a	n/a	n/a	n/a	n/a	n/a	Common

SUPPLEMENTARY TABLE 2: Maximum gas measurements from BJP-1 before and after the Yogyakarta earthquake (~6:00am 26/5/2006; separated by thick lines)[7]. n/a indicates data not available.

Date (May 2006)	Total Gas (%)	C_1 (ppm)	C_2 (ppm)	C_3 (ppm)	iC_4 (ppm)	nC_4 (ppm)	iC_5 (ppm)	nC_5 (ppm)	CO_2 (ppm)	H_2S (ppm)
6am 25/5 – 6am 26/5	6.5	57816	4212	1753	65	60	24	13	868	0
6am 26/5 – 6am 27/5	8.3	75024	4949	2034	91	74	34	22	593	25
6am 27/5 – 6am 28/5	1.6	14445	685	197	20	11	6	5	354	0
Kick (730am 28/5)	20	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	500

Methodology for Drilling Mud Gas Analysis

Gas amounts contained within drilling mud are routinely and continuously measured during hydrocarbon drilling operations for safety reasons (e.g. detection of potentially harmful or explosive gases, such as H_2S and methane) and to provide information on pore fluid content (e.g. hydrocarbons)[9]. Drilling mud is continuously circulated through the borehole whilst drilling. Mud is first pumped down through the drill string to the bit, and back to the surface via the annular space between the string and wellbore wall. As drilling mud flows up the wellbore annulus, subsurface gases flow into the mud through direct diffusion out of formations exposed by the wellbore, and through release of gasses trapped within drilled material ('cuttings')[9]. The drilling mud passes through gas separation equipment at the surface, and chromatography is used to precisely measure the amounts of hydrocarbon and other gases[9]. Additional gas sensors are also deployed around the drill rig (such as at the wellhead and shale shakers) for safety reasons, and to provide supporting data for gas analysis[9].

The amount of formation gas observed in drilling mud is a function of the rock being drilled (hydrocarbon content, porosity, permeability), the rate of penetration (faster drilling yields more drilled material and more gases in the mud), mud circulation rate (higher rate provides less time for gas to diffuse into mud), differential pressure (mud pressure minus pore pressure; higher differential pressure results in less gas flow into wellbore), mud type (formation gas is highly soluble in oil-based mud, as used in BJP-1) and hole diameter (higher gas readings due to larger wellbore surface area)[9]. Rock type, rate of penetration and mud circulation rate are the main controls on mud gas chemistry in BJP-1, as other parameters were all approximately constant in the open wellbore[7,8], although the Kalibeng clay displays zones of significant borehole enlargement compared to the underlying volcanic and volcaniclastic sequences[8]. In particular, mud pressure in BJP-1 was approximately equal to the pore fluid pressure during drilling of the entire open wellbore section[7], providing ideal conditions for formation fluids to enter the borehole (Mouchet and Mitchel, 1989).

Mud gas readings are higher in the Kalibeng clays than in the volcanic/volcaniclastic sequences due to its high porosity (35-50%) and organic material content[1,8], which also allowed for higher rates of penetration[7,8]. Comparison of daily gas readings must also consider that only ~7 hours of drilling operations took place after the earthquake[4,7,8]. Drilling operations were halted following total mud losses (of between 20670-73458 liters, or 10-36% of total hole volume[7,8]), after which the well was refilled with drilling mud, circulated slowly for several hours and the process of removing the drill string from the hole was initiated[7,8]. The cessation of drilling operations may have resulted in the observed lower maximum gas readings in the 24 hours after the earthquake because less drilled rock material was collected, and thus no further cuttings gas would be present after the losses at final depth. However, this is significantly offset by the lower average circulation rate while pulling out of hole, in which the drilling mud was allowed to sit static and absorb formation gases for extended periods[7,8]. Drilling mud was circulated 8 times whilst pulling out of the hole, with the well left static for intervening periods of between 24 to 98 minutes (with an average of 57 minutes)[7]. The rapid movement of the drill bit and drill collars whilst pulling out of the hole may also cause localized suction pressures inside the wellbore ('swabbing'), which may have pulled more formation fluid and gas into the well[4,10]. It is uncertain whether swabbing occurred in BJP-1. Swabbing is often associated with increased force required to pull the drill string out of the hole, and Sawolo et al. (2009) cite "no apparent drag" as evidence that swabbing did not occur[6], but this is contradicted by original drilling reports that state "pipe worked from 2652-2591m" and "overpull increasing"[7], and thus may indicate swabbing. Overall, the reduced average circulation rates and possible swabbing effects are expected to offset any reduced gas levels from the absence of drilled cuttings after the total losses. Furthermore, none of the observed drilling parameters or conditions would mask or obscure liquefaction-induced gas release into the wellbore. Indeed, the conditions in BJP-1 were extremely well suited for detecting any gas release from the Kalibeng clays following the earthquake, as these effects would be expected to be at least as large, and likely much greater than, the gas measurements observed during drilling of the clays.

It is important to note that earthquake-triggered liquefaction of the Kalibeng clay would have been expected to result in other observable effects in BJP-1, in addition to increased gas amounts. Liquefaction or remobilization of the clays would cause clay to move into the wellbore, which would result in clay cavings being observed at the surface and may also cause the drill string to be difficult to pull out of the hole through the clays. However, no observations of clay material were reported following the earthquake, and the only wellbore instability observed was in the volcanics and volcaniclastics in the bottom 300 meters of the well (possibly due to swabbing), and then immediately following the major kick (26 hours after the earthquake)[7,8].

An effective stress drop due to the earthquake[2], or even direct fault reactivation[1,7], might be associated with loss of drill mud into the formation. Indeed, it has been claimed that 3180 liters of mud were lost into the formation approximately seven minutes after the Yogyakarta earthquake (6:02am)[1,7]. These minor losses could correlate with the arrival of earthquake seismic waves at the Lusi location, and thus may be an indication of an effect of the earthquake on the BJP-1 well[1,2,7]. However, there is significant uncertainty over the reported time of these losses[8], with the original data[7] alternatively indicating that these losses may have occurred at ~5:00am[8], and clearly identifying that the losses occurred when drilling at 2827 meters depth, which corresponds to the drilling depth at ~05:00am[7]. Thus, there is strong evidence that these minor losses in BJP-1 occurred approximately one hour before the earthquake[8]. Furthermore, it has been noted that the total losses at the bottom of the well occurred "less than two hours after two major aftershocks", and that "the proximity of the times suggest that the earthquake had an impact down hole in the well"[7]. Yet, it is highly uncertain whether there is any direct correlation between the three large aftershocks following the main Yogyakarta earthquake (Mw4.4 at 8:07am, Mw4.8 at 10:10am and Mw4.6 at 11:22am) and the total losses (at 12:50pm) that occurred between 90 and 280 minutes afterwards[7], particularly given their significantly smaller size (compared to the main shock) and the large distance (~260 km) to the Lusi location[3,4] (Manga, 2007). Finally, it is interesting to note that, whilst there are no reliable indications of clay liquefaction in the 24 hours following the Yogyakarta earthquake, there are numerous indications of Kalibeng clay activity associated with the major drilling kick in BJP-1. Observations during and after the kick include high gas flows (20% gas), wellbore instability (bit stuck, drill string packed-off), significant volumes of formation material migrating into the casing, pore fluid influxes, drilling mud losses and evidence of direct communication between BJP-1 and the Lusi main vent[4,7,8,10]. Hence, there is extensive evidence from the BJP-1 well that liquefaction, remobilization or entrainment of the Kalibeng clay occurred prior to, and during the first days of, the Lusi eruption, but these appear to be in response to the drilling kick in BJP-1.

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